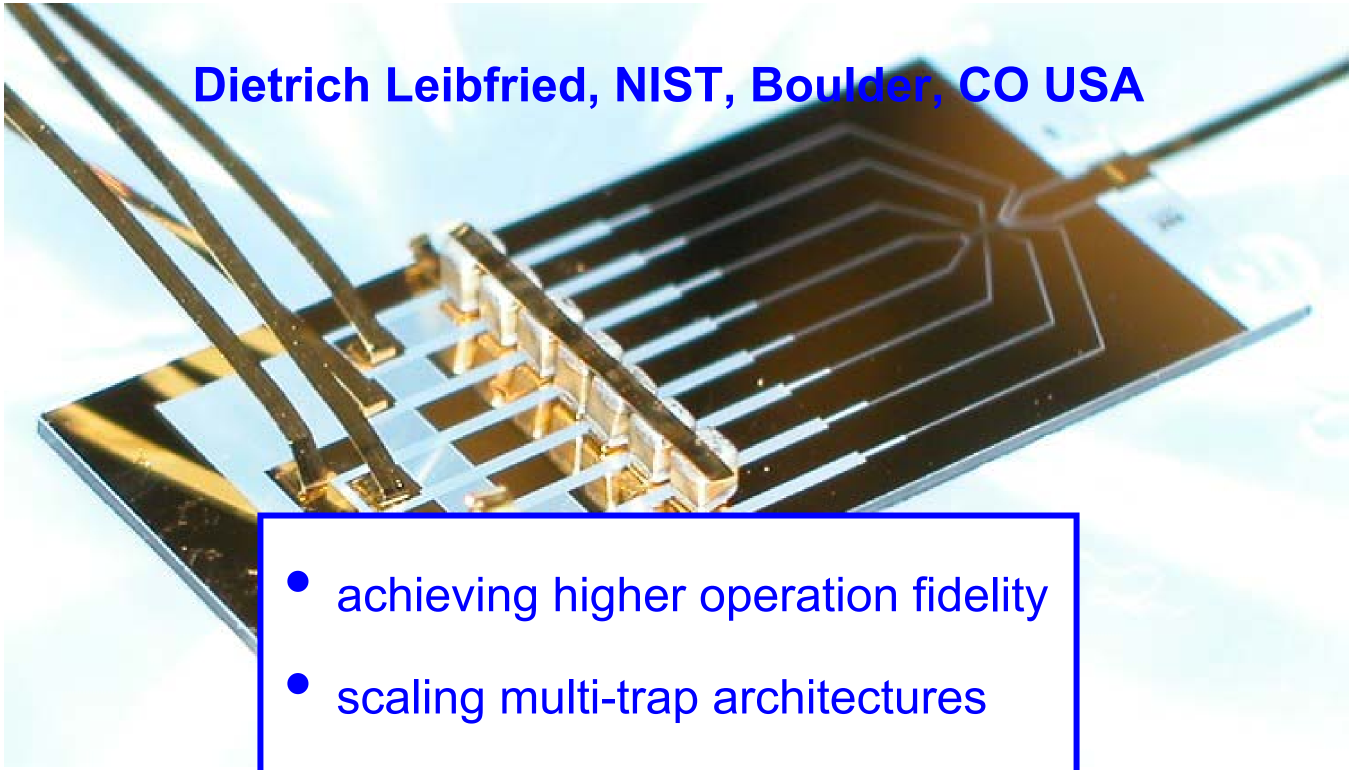
Challenges for ion trap quantum computing



Dietrich Leibfried, NIST, Boulder, CO USA

- achieving higher operation fidelity
- scaling multi-trap architectures
- large scale classical control
- fault tolerance

ARDA NIST

NIST ion storage group

(April 26 2005)

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Rainer Reichle (postdoc, Freiburg)
Till Rosenband
Signe Seidelin (postdoc, Orsay)
Janus Wesenberg (postdoc, Aarhus)
David Wineland

DiVincenzo requirements

I. A scalable physical system with well characterized qubits

II. The ability to initialize the state of the qubits to a simple fiducial state

optical pumping, ground-state cooling (99.9%)

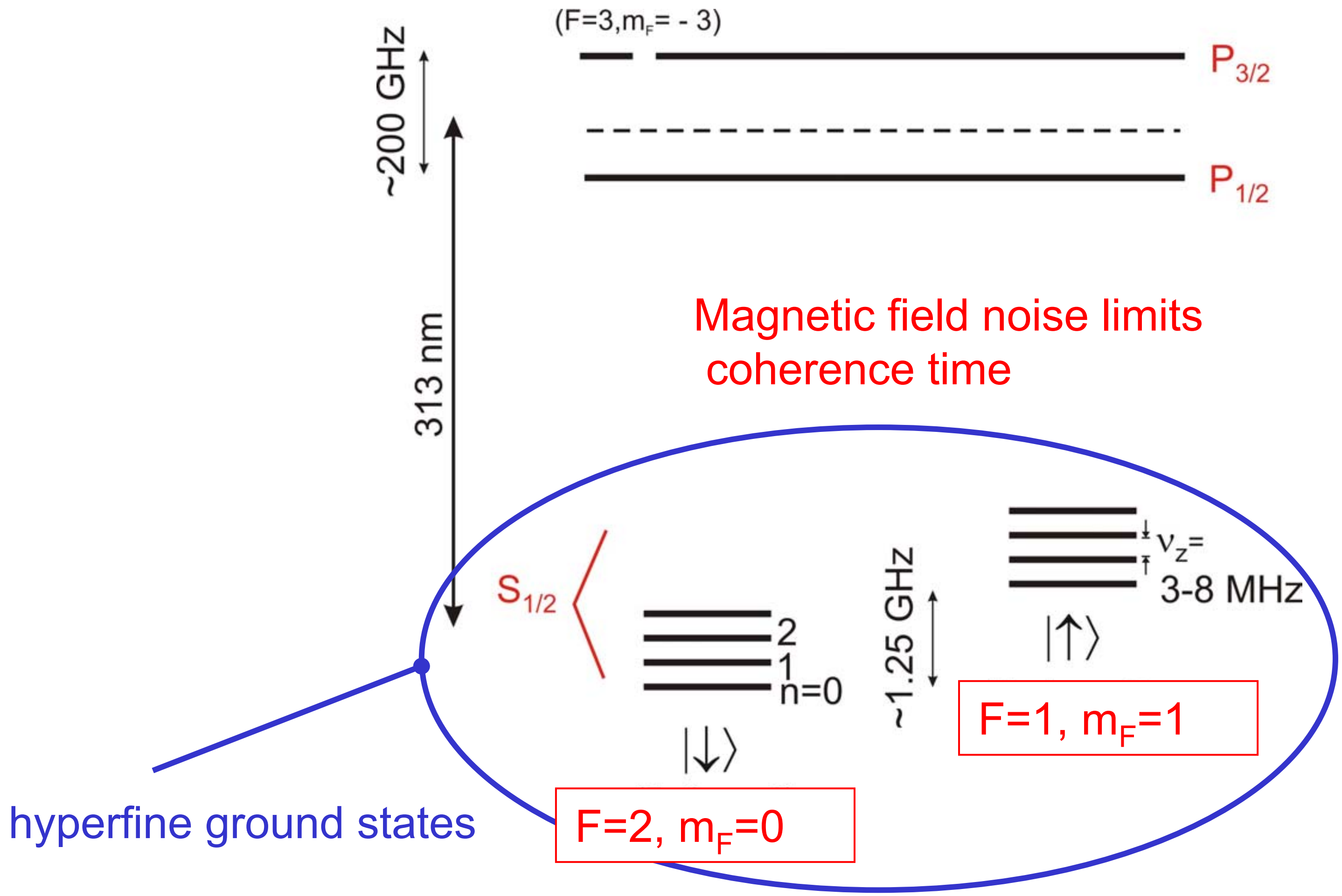
III. Long relevant decoherence times, much longer than the gate time

Hyperfine ground states

IV. A universal set of quantum gates (single qubit rot., two qubit gate)

V. A qubit-specific read out capability

Example ion qubit: $^9Be^+$



Low memory error qubits

optical qubits:

state lifetimes < conceivable computation time $\Rightarrow$ spontaneous emission errors, hard to correct

coherence times limited by laser and environ. $\Rightarrow$ memory phase errors

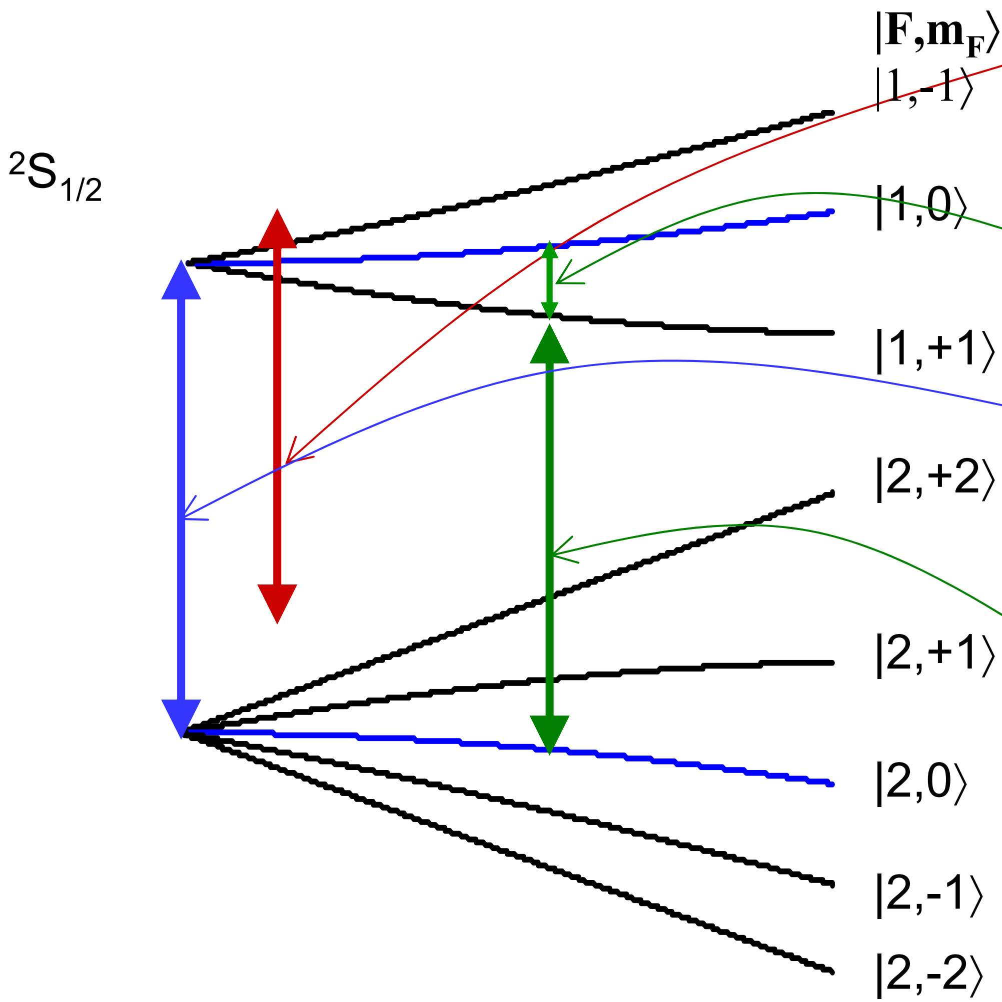
hyperfine qubits:

state lifetimes >> conceivable computation time $\Rightarrow$ no intrinsic bit flip errors

coherence times depend on environment $\Rightarrow$ memory phase errors dominate

Low memory error qubits

magnetic field dependence:



$|2,2\rangle \leftrightarrow |1,1\rangle$
$\delta f/\delta B = -2.1$ MHz/G
for $\delta B = 1$ mG
$\tau_2(\delta\phi = 1 \text{ rad}) \cong 76\ \mu s$

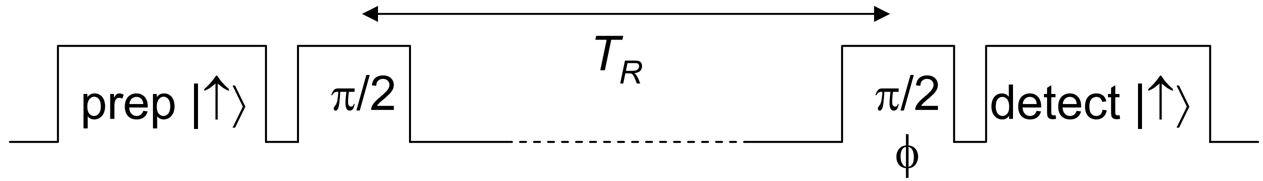
Substantial level splitting
$\Rightarrow$off-resonant excitations suppressed

$|2,0\rangle \leftrightarrow |1,0\rangle$
field-independent at $B = 0$
m_F levels are degenerate

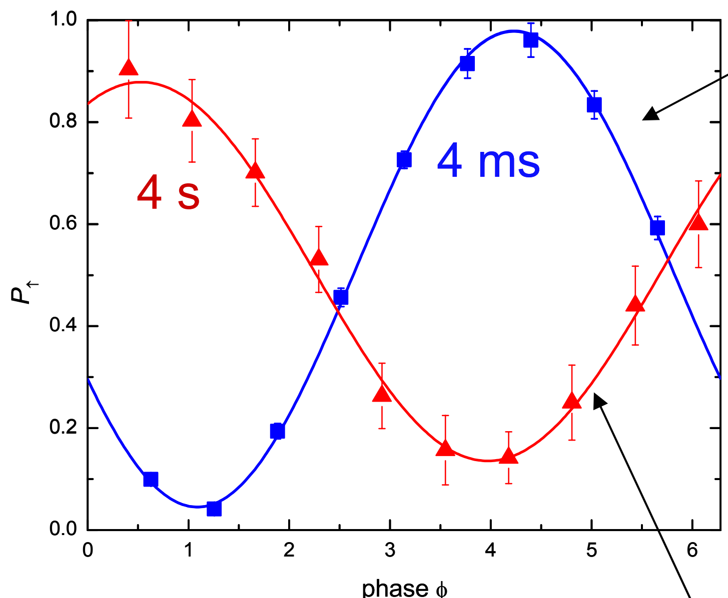
$|2,0\rangle \leftrightarrow |1,1\rangle$
$\frac{1}{2}\, \delta^2 f/\delta B^2 = 3$ kHz/G²
for $\delta B = 1$ mG
$\tau_2(\delta\phi = 1 \text{ rad}) \cong 53$ s

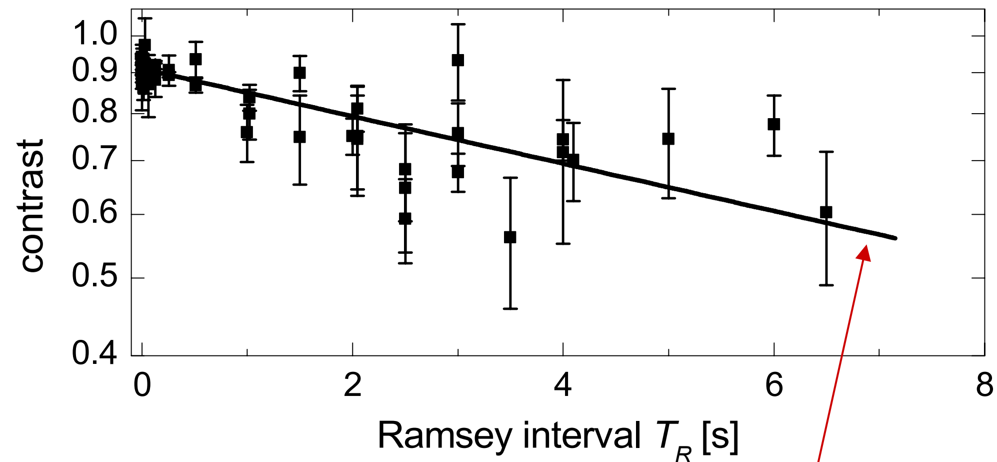
Robust memory coherence times

Ramsey experiment:



contrast 0.93(1)





contrast 0.74(4)

Coherence time 14.7 ± 1.6 s

Ratio of coherence time to error correction time: $\epsilon \sim 10^{-5}$

C. Langer *et al.*, PRL **95** 060502 (2005), see also poster M01

DiVincenzo requirements

I. A scalable physical system with well characterized qubits

II. The ability to initialize the state of the qubits to a simple fiducial state

optical pumping, ground-state cooling (99.9%) ✓

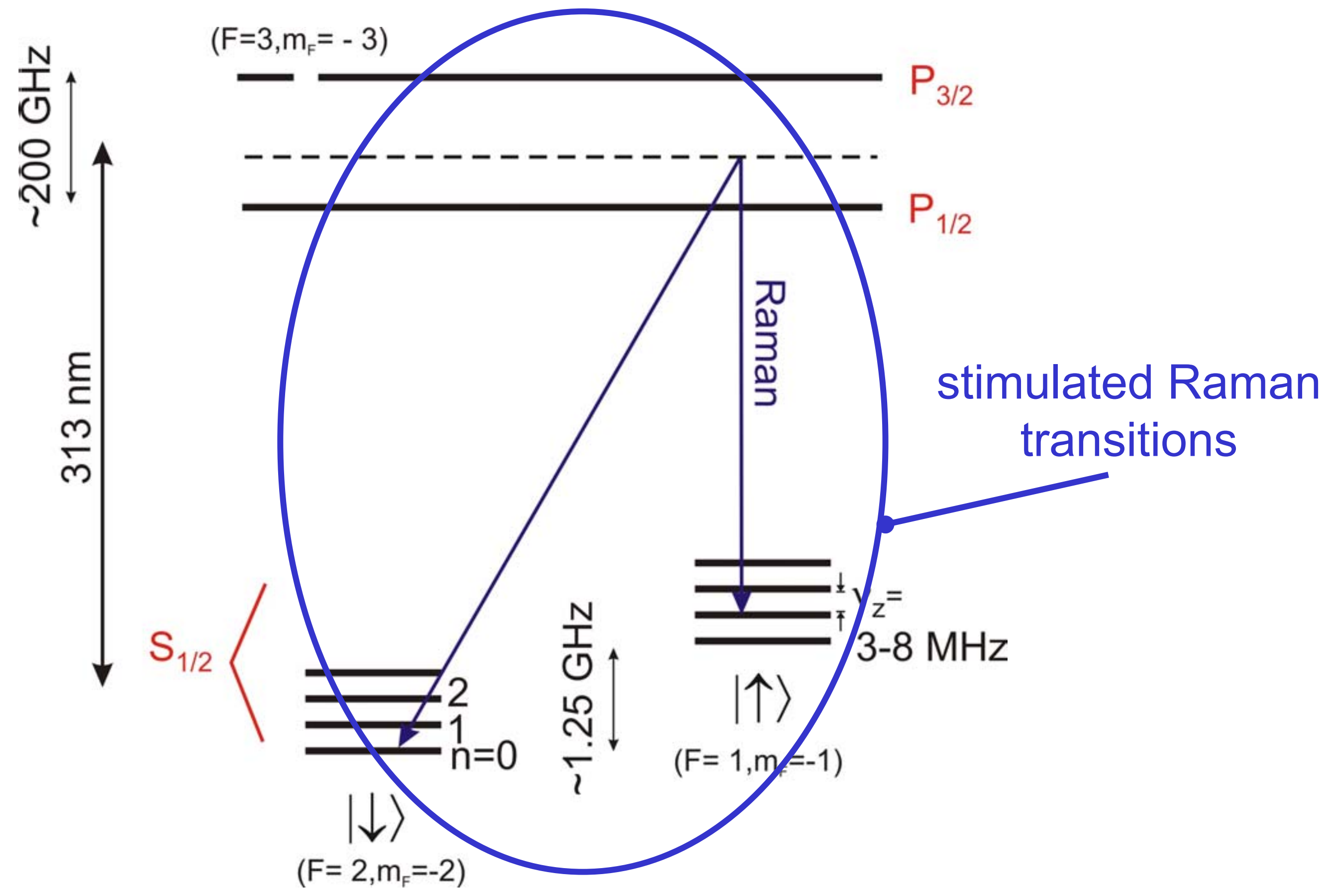
III. Long relevant decoherence times, much longer than the gate time

Hyperfine ground states T_{dec}> 10 **sec** demonstrated ✓

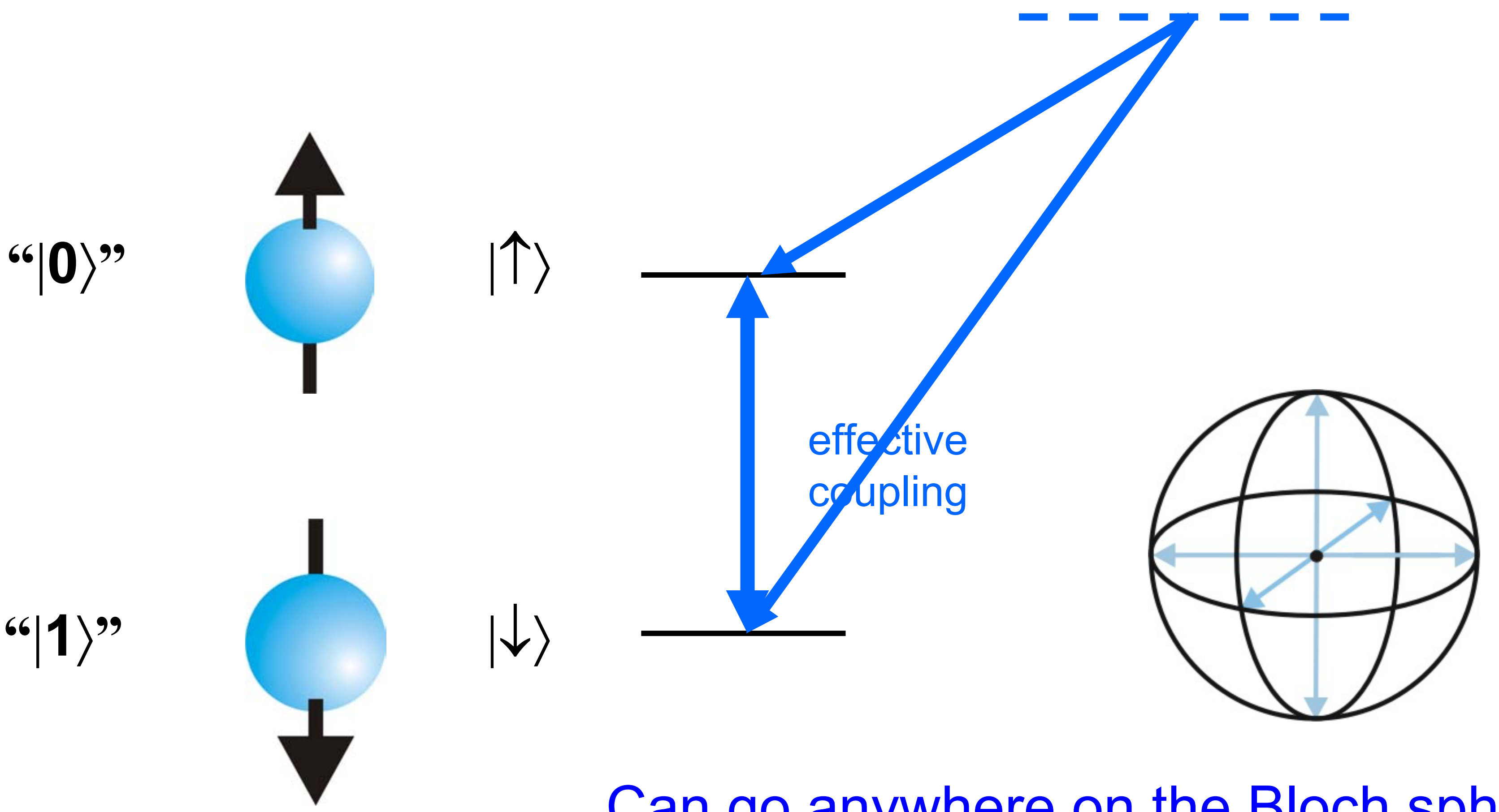
IV. A universal set of quantum gates (single qubit rot., two qubit gate)

V. A qubit-specific read out capability

Single qubit rotations



Single qubit rotation: stimulated Raman transitions



Can go anywhere on the Bloch sphere

Typical π-pulse time:1 μs

Fidelity: >99%

Boosting fidelity in single qubit rotations

Main obstacles to single qubit rotation errors $\approx 10^{-4}$:

1) Frequency errors, negligible in Raman transitions
2) Intensity errors, currently order 5%, need to be reduced to $<10^{-2}$
3) Errors due to spontaneous emission, need to be reduced to $<10^{-2}$

Possible improvements for 2):

- Quieter laser systems, intensity stabilization, active feedback

- Use microwaves to drive single-qubit rotations
  (new issues with cross talk and addressing, especially on large array chips)

Possible improvements for 3):

- Go to larger detunings, requires more powerful laser systems (see poster M20)

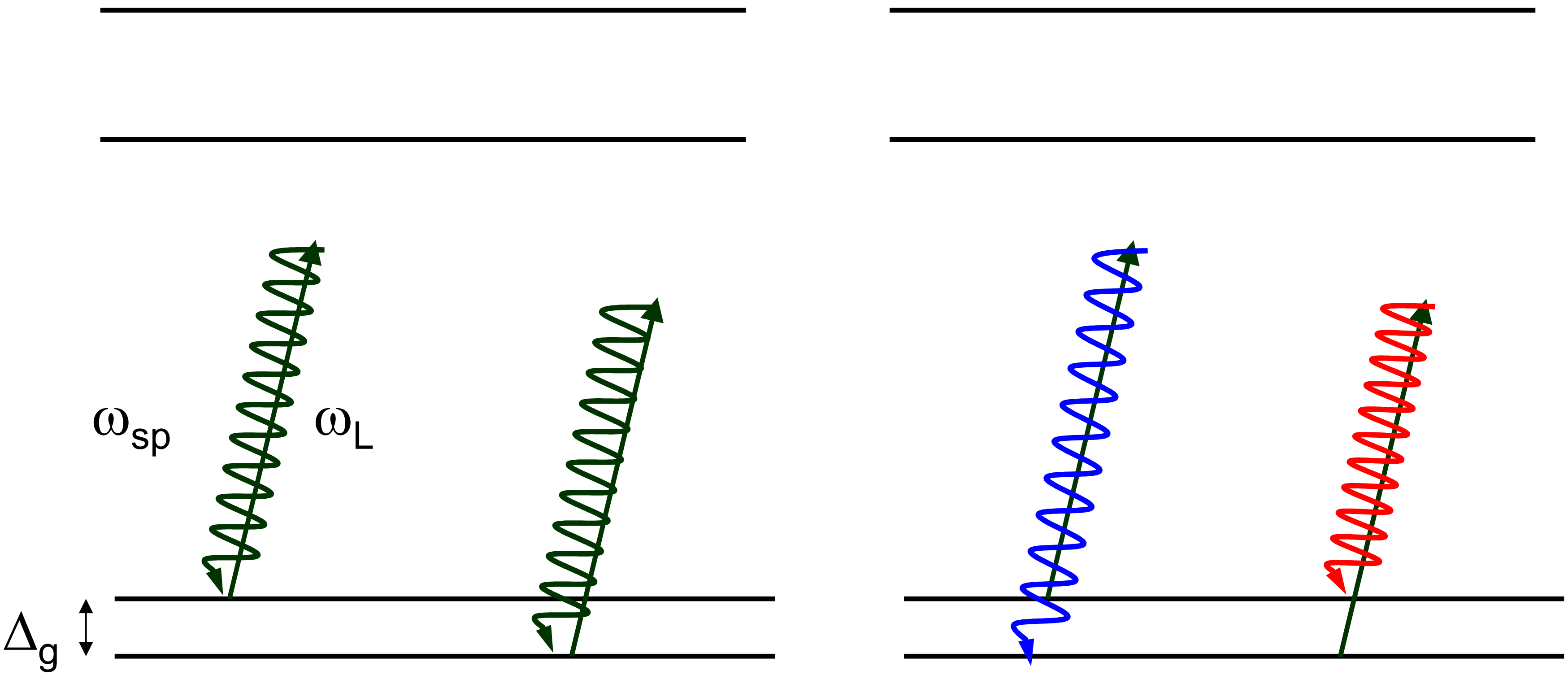
- Use microwaves to drive single-qubit rotations

Spontaneous scattering

Several hyperfine ground states:

Rayleigh elastic scattering

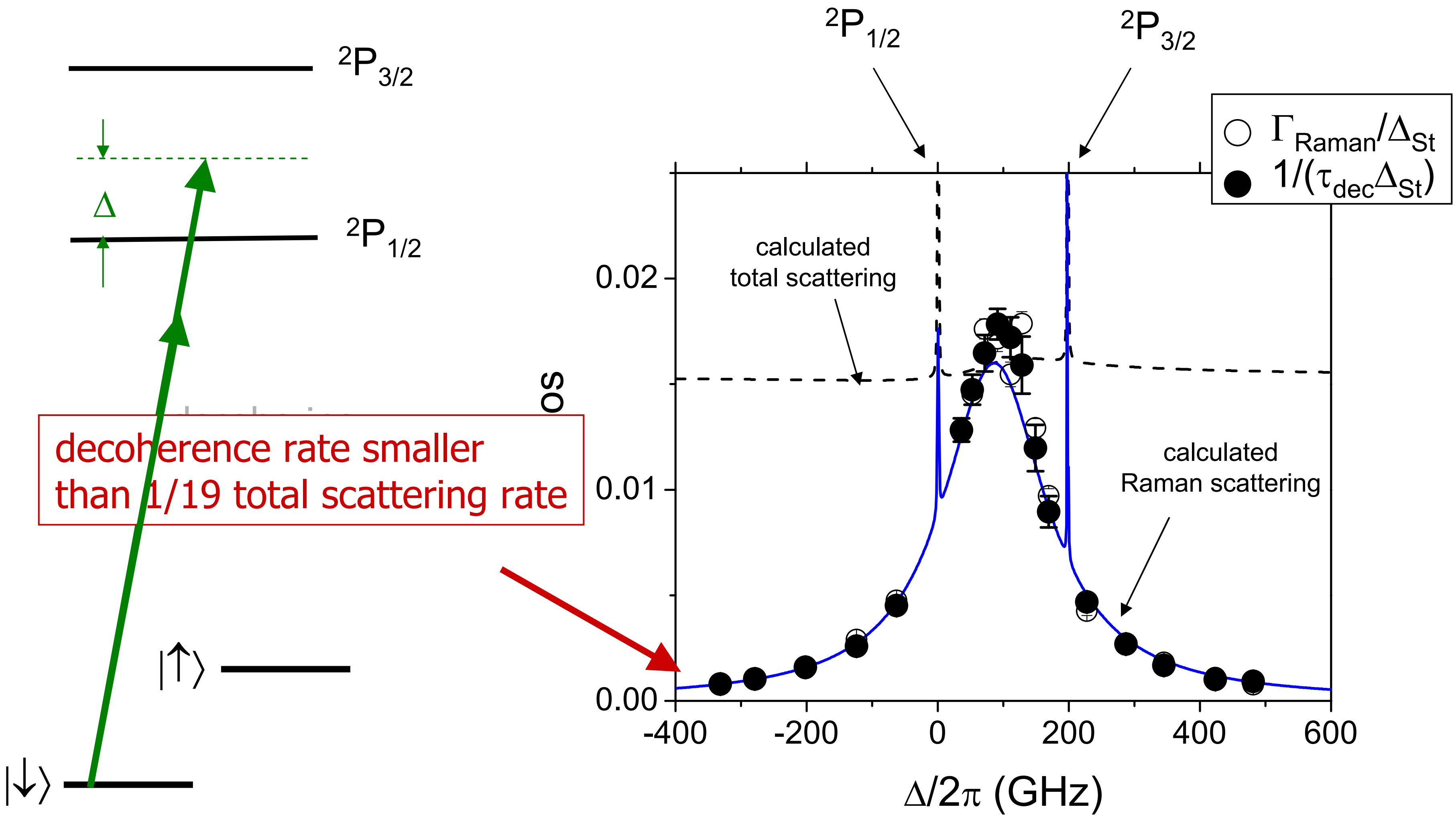
Raman inelastic scattering



No information about the internal state of the atom is carried out by the scattered photon.

Scattered photon frequency and polarization are entangled with the atoms' internal state.

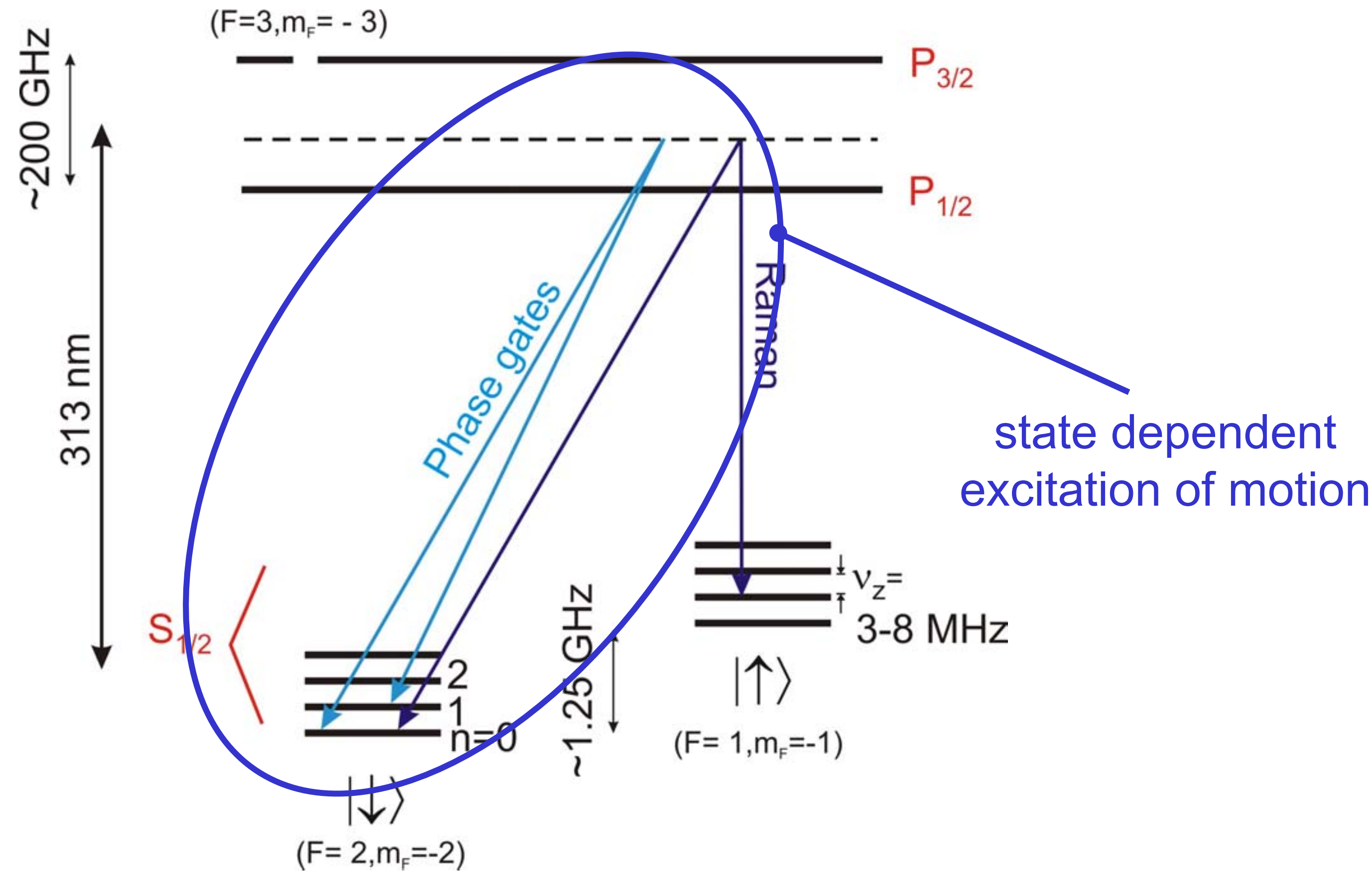
Decoherence vs. detuning



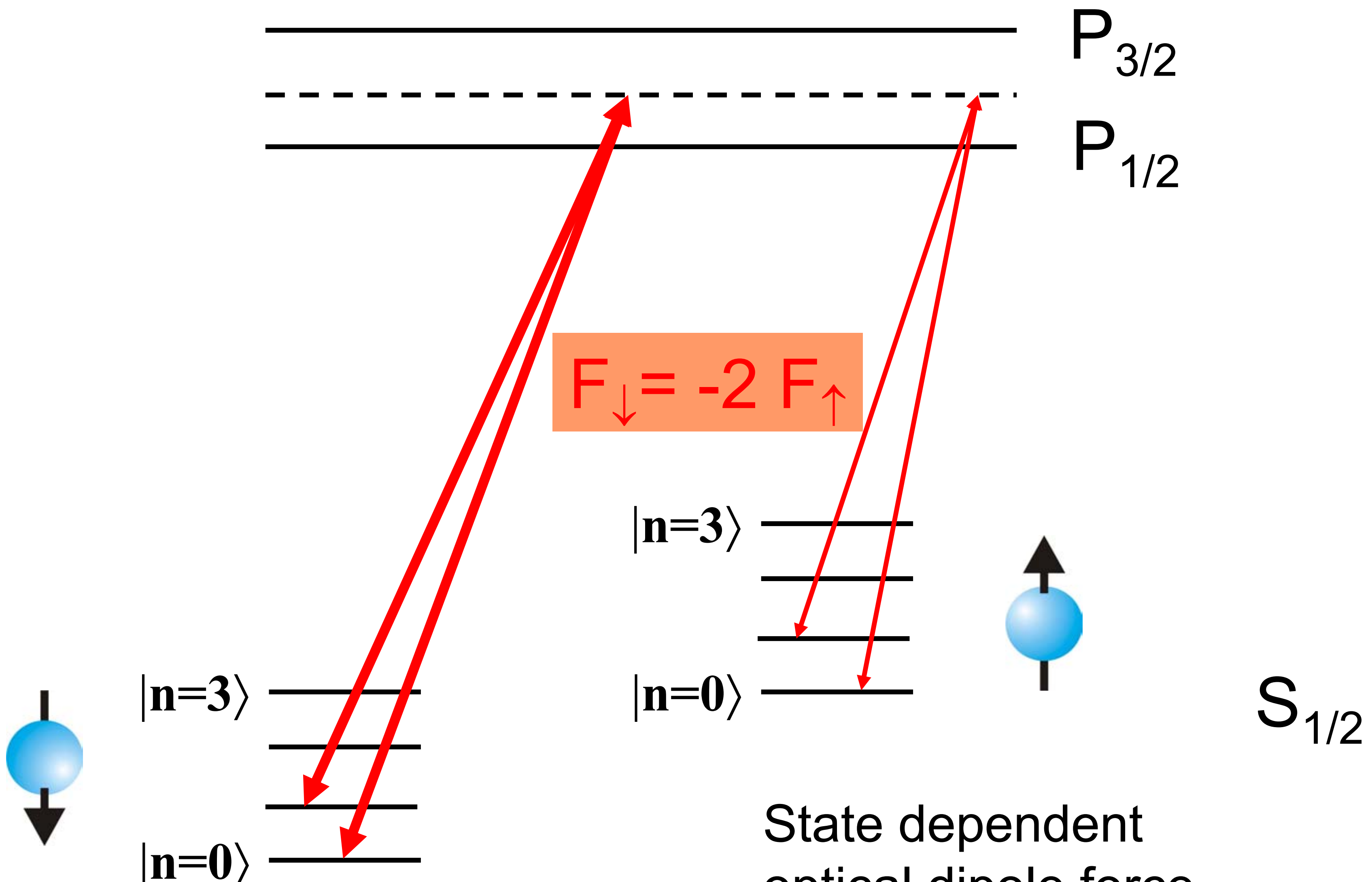
Raman scattering reduces as Δ^2 when $\Delta > \Delta_f$ largely independent of FS splitting

R. Ozeri, et. al. Phys. Rev. Lett. **95** 030403 (2005), see also poster M20.

Two qubit gates

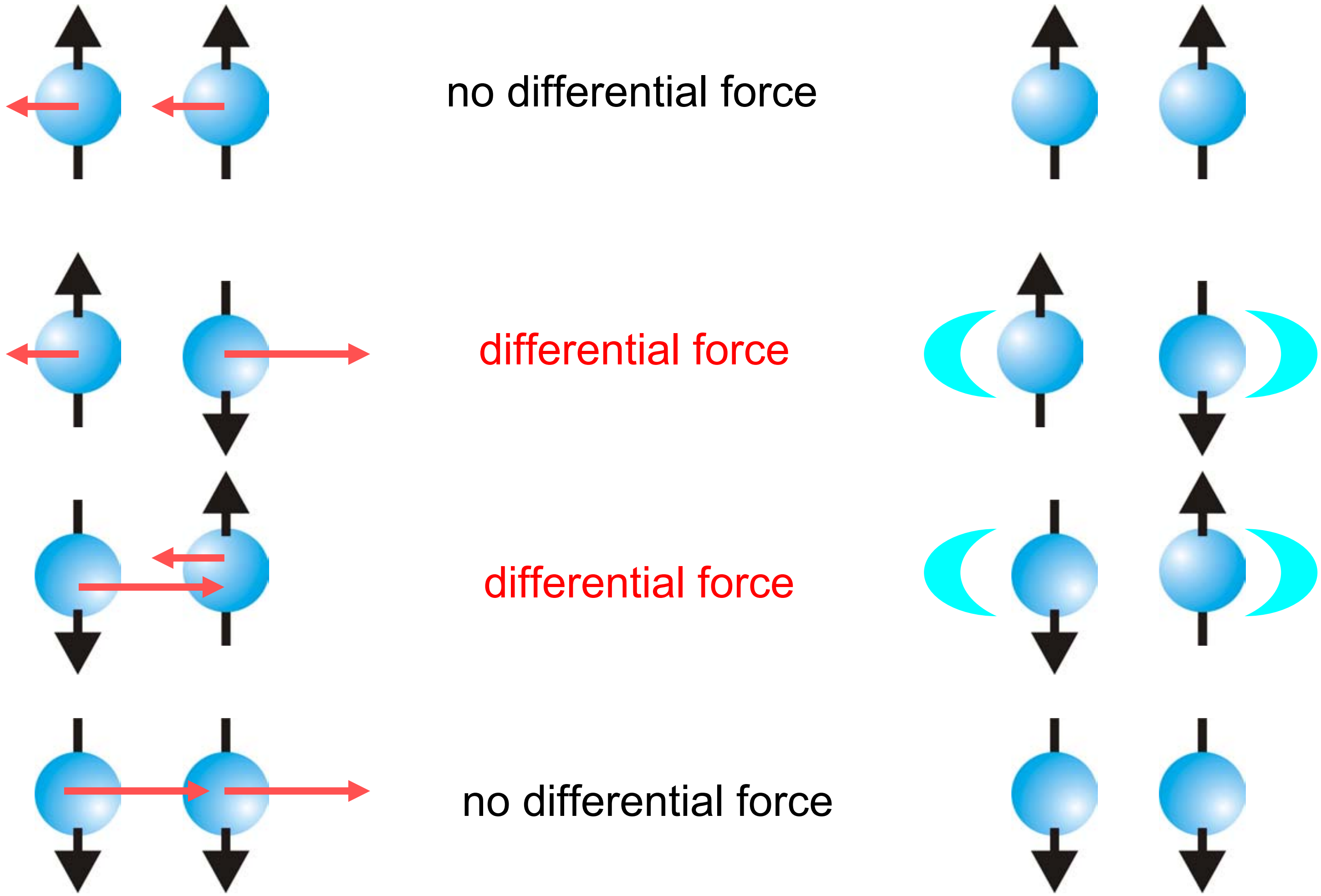


Motional excitation



State dependent optical dipole force

Stretch mode excitation



Phase gate truth table and properties

$$
\begin{aligned}
|\downarrow\downarrow\rangle &\rightarrow |\downarrow\downarrow\rangle \\
|\downarrow\uparrow\rangle &\rightarrow e^{i\phi}|\downarrow\uparrow\rangle \\
|\uparrow\downarrow\rangle &\rightarrow e^{i\phi}|\uparrow\downarrow\rangle \\
|\uparrow\uparrow\rangle &\rightarrow |\uparrow\uparrow\rangle
\end{aligned}
$$

Gate fidelity: 97%
Gate time: 7 μs (ca. $25/\nu_{COM}$)

D. Leibfried *et al.*, Nature **422**, 414 (2003)
Theory: Milburn, Sørensen&Mølmer

Boosting fidelity in two-qubit gates

Main obstacles to two-qubit gate errors $\approx 10^{-4}$:

1) Motional frequency errors due to trap potential fluctuations
2) Intensity errors, currently order 5%, need to be reduced to $<10^{-2}$
3) Errors due to spontaneous emission, order 2%, need to be $<10^{-4}$
4) Z-phase gates only work on field dependent sub-states, MS gates o.k.

Possible improvements:

1) Quieter electrode control systems, minimize stray charges and other perturbations

2) Quieter laser system, active feedback on laser intensity
3) More powerful lasers (can then go to larger detuning, see Poster M20)

4) Use Mølmer-Sørensen type gate or momentarily transfer out of field independent state(s).

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Hyperfine ground states T_{dec}> 10 **s** demonstrated ✓

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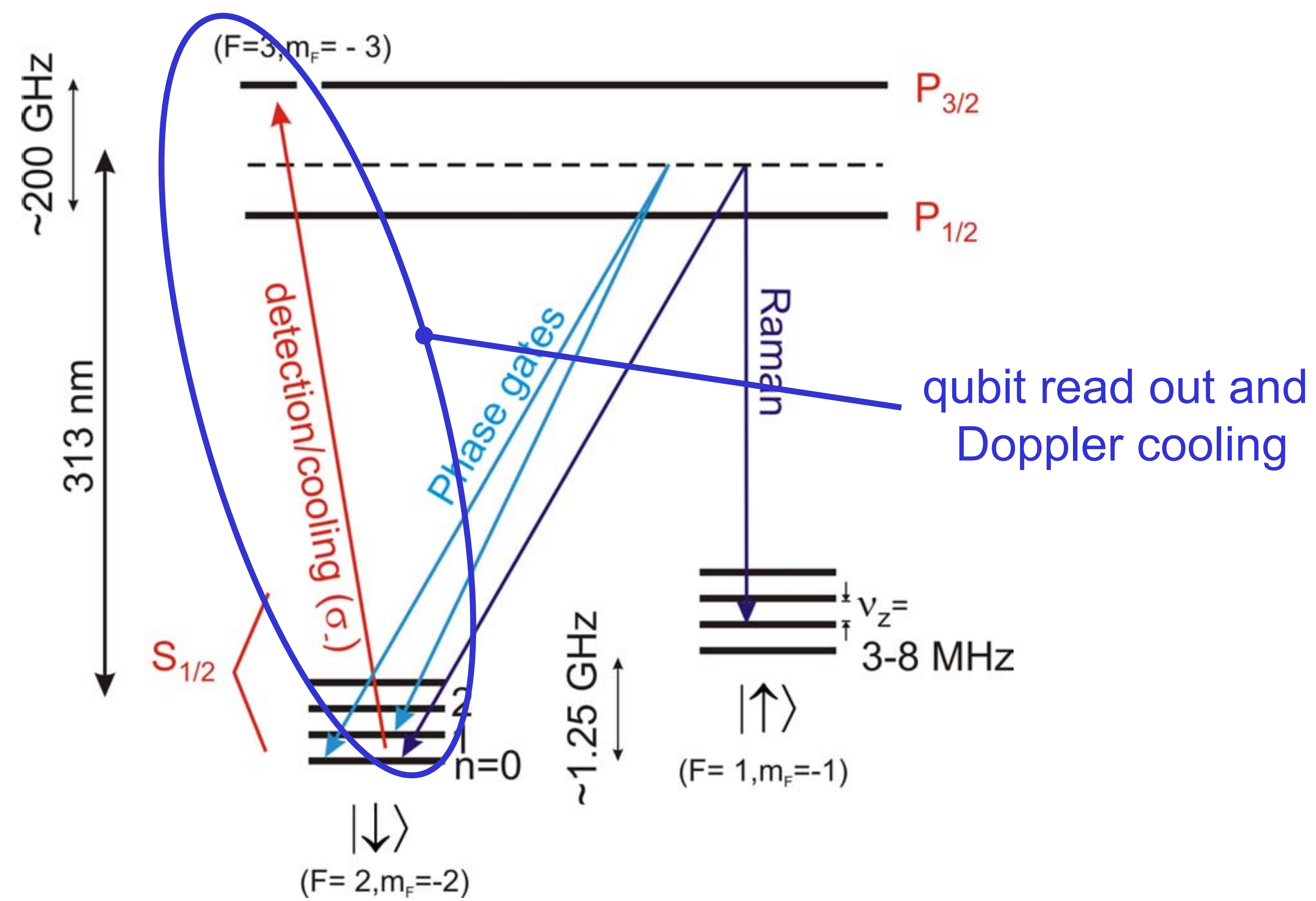
co-carrier rotations, phase gate ✓

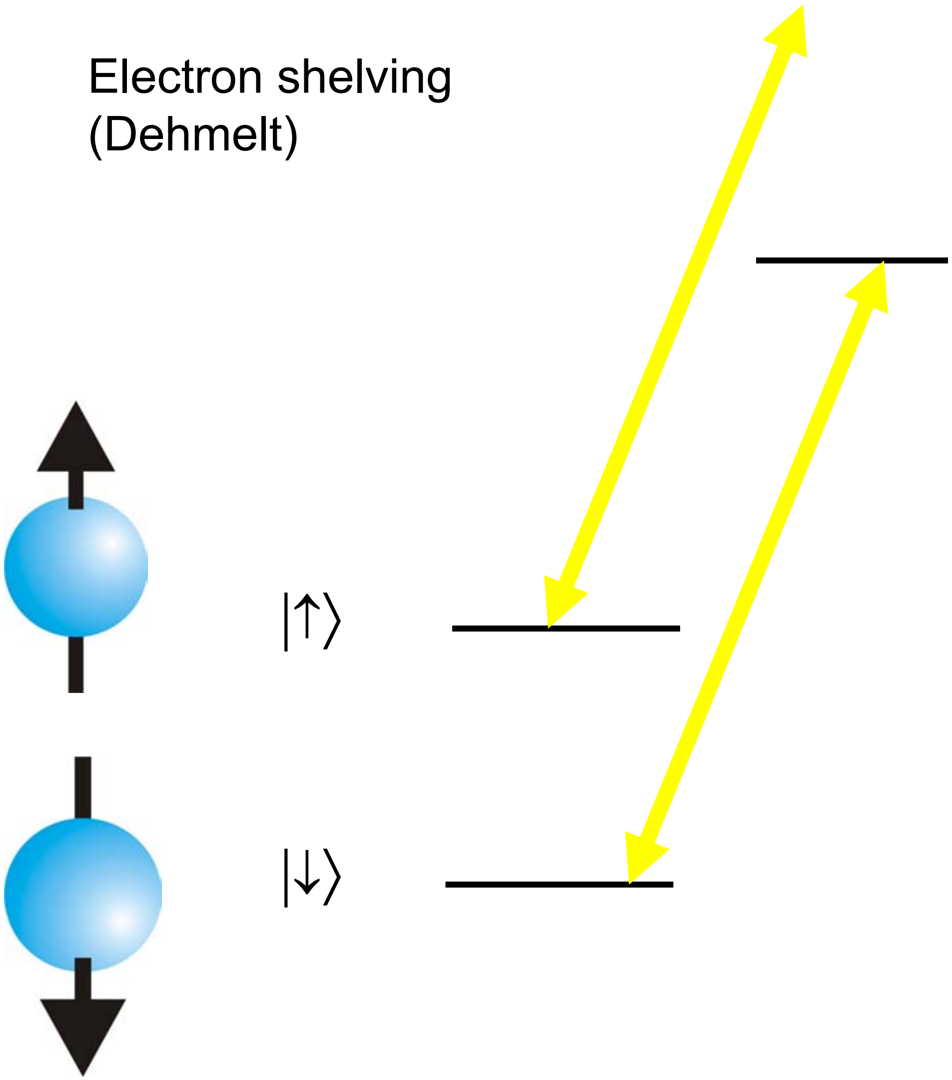
V. A qubit-specific read out capability

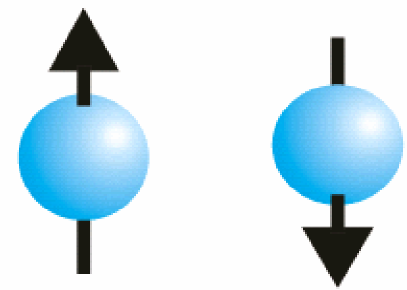
Example qubit: $^9Be^+$



Qubit readout

Electron shelving
(Dehmelt)





Be^+ (NIST):
200 μs detection period
10 counts in $|\downarrow\rangle$
0.1 counts in $|\uparrow\rangle$
>99% state discrimination

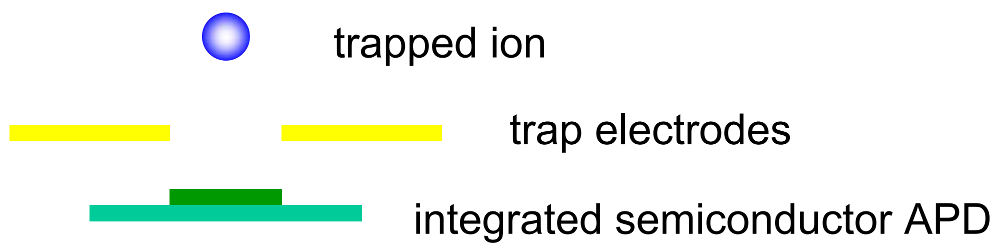
Scale-up of qubit readout

Currently read-out is based on bulky high NA free-space optics.

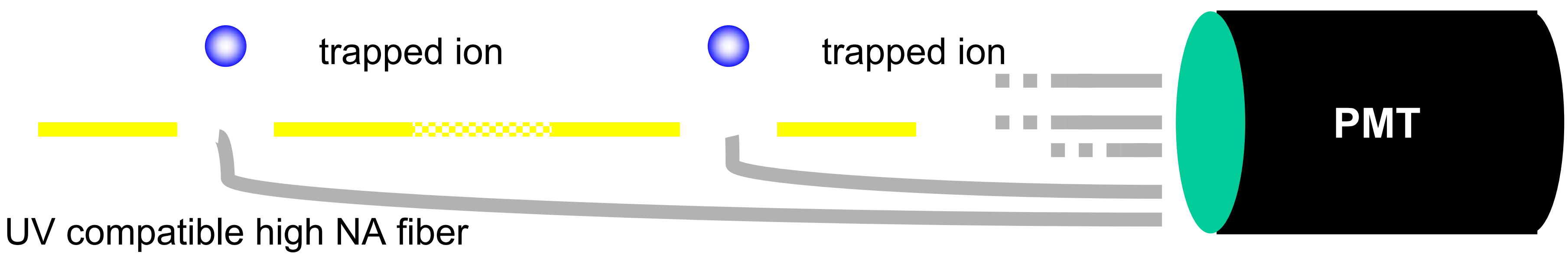
Parallel, fault tolerant architecture requires multi-zone readout.

Will need specialized detection schemes:

i) On chip optics-free detectors (see also M. Crawford and J.S. Kim)



ii) On chip fiber-bundle multiplexing to external PMT(s) (only quasi-parallel)



DiVincenzo requirements

I. A **scalable** physical system with well characterized qubits

II. The ability to initialize the state of the qubits to a simple fiducial state

optical pumping, ground-state cooling (99.9%) $\Rightarrow |\downarrow\downarrow\downarrow\downarrow\ldots\rangle\ |0\rangle$ ✓

III. Long relevant decoherence times, much longer than the gate time

T_{dec}> 10 s, T_{gate}=10 μs, heating irrelevant ✓

IV. A universal set of quantum gates (single qubit rot., two qubit gate)

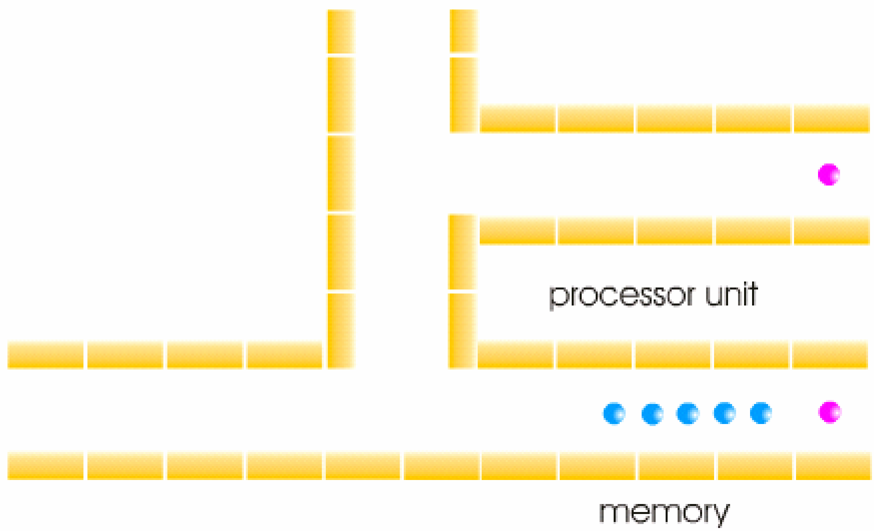
co-carrier rotations, geometric-phase gate, heating tolerable ✓

V. A qubit-specific read out capability

electron shelving method, 99% readout efficiency (100%) ✓

NIST Multiplexed trap architecture

extension of J. I. Cirac and P. Zoller, PRL **74,** 4091 (1995).



D. J. Wineland, *et al.*,
J. Res. Nat. Inst. Stand. Technol. **103**, 259 (1998);
D. Kielpinski, C. Monroe, and D. J. Wineland,
Nature **417**, 709 (2002).
Other proposals: DeVoe, Phys. Rev. A **58**, 910 (1998) .
Cirac & Zoller, Nature **404**, 579 (2000), Duan *et al.*

interconnected multi-trap structure
subtraps completely decoupled

routing of ions by controlling electrode voltages

processor sympathetically cooled
only need to cool three normal modes
no need for ground state cooling in memory

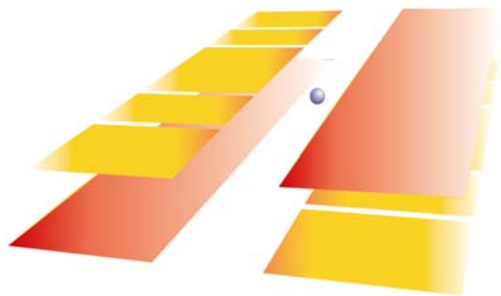
no individual optical addressing during two-qubit gates
can do gates in tight trap

one-qubit gates in extra subtrap
ion is strongly confined and easily addressed

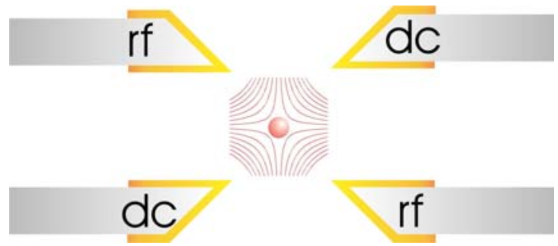
readout in extra subtrap
no rescattering of fluorescence

Two layer Paul trap

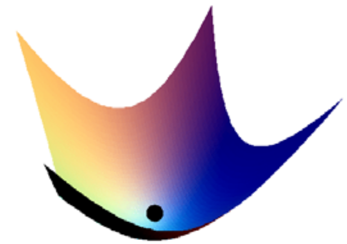
radial confinement:



radial cross section



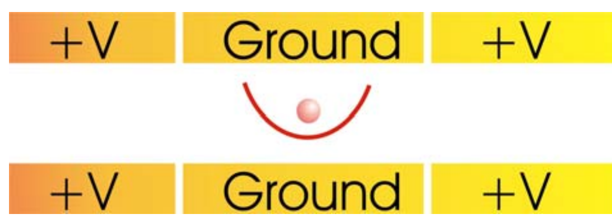
ac quadrupole field



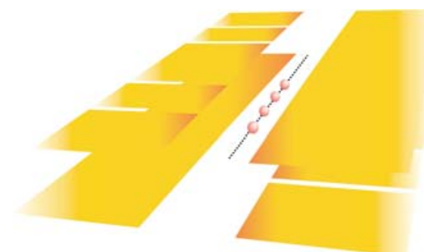
harmonic time averaged
pseudo-potential

axial confinement:

axial cross section

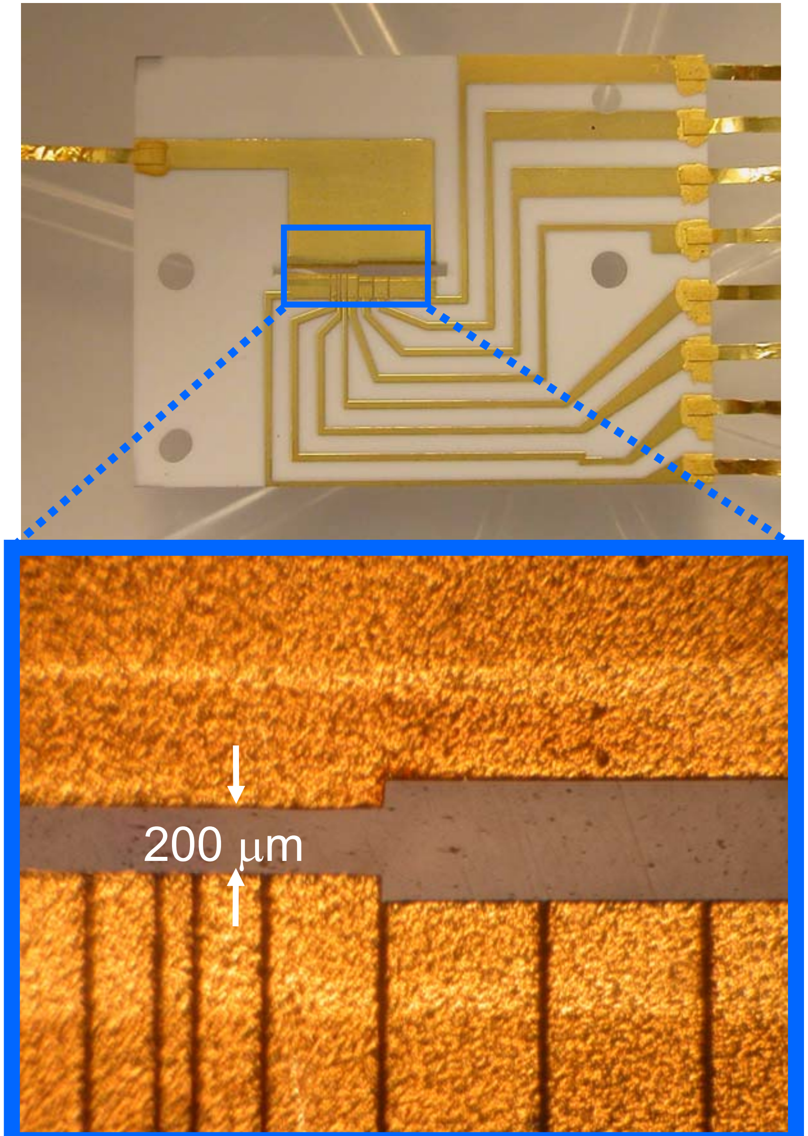


static harmonic axial potential

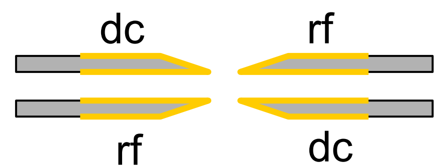


radial conf. >> axial conf.
$\Rightarrow$ ions align along trap axis

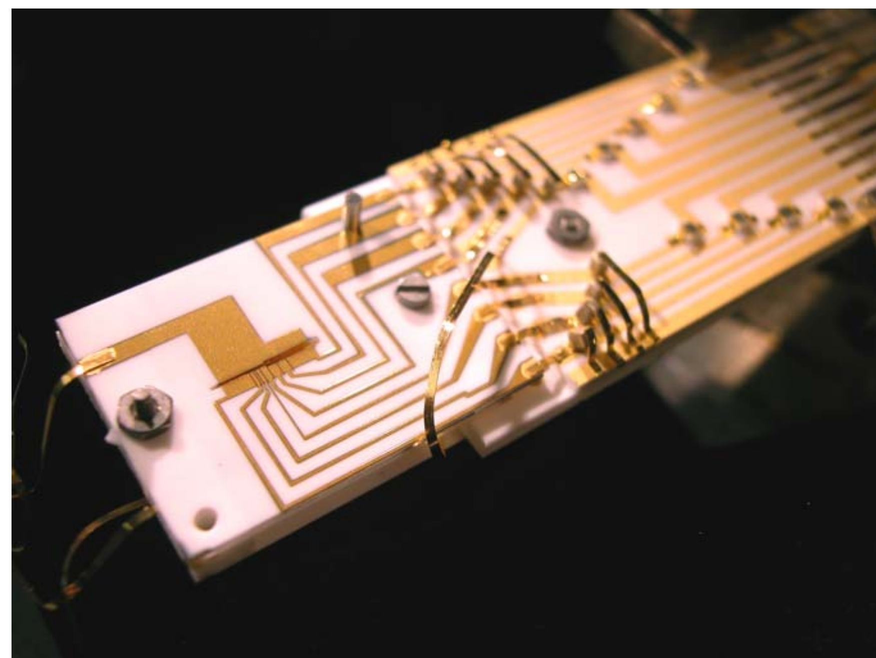
Two Layer Trap Technology



2 wafers of alumina (0.2 mm thick)
gold conducting surfaces (2 μm)



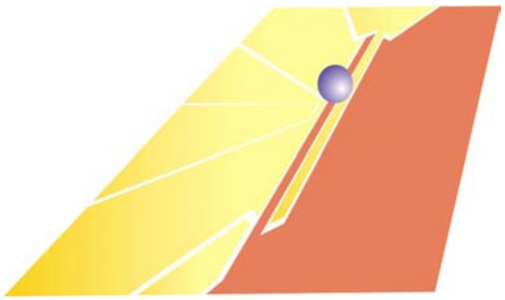
6 zones, dedicated loading zone



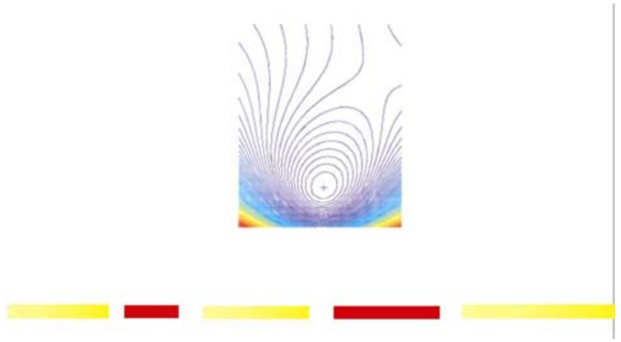
Murray Barrett/John Jost

Surface trap

radial confinement:

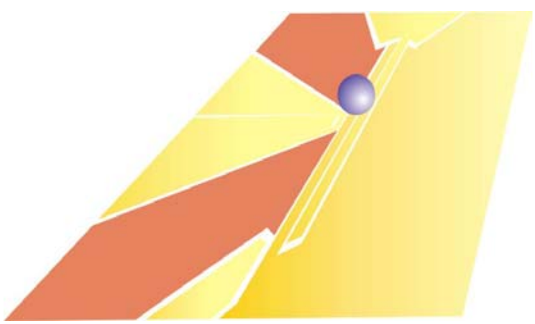


radial cross section



time averaged pseudo-potential

axial confinement:

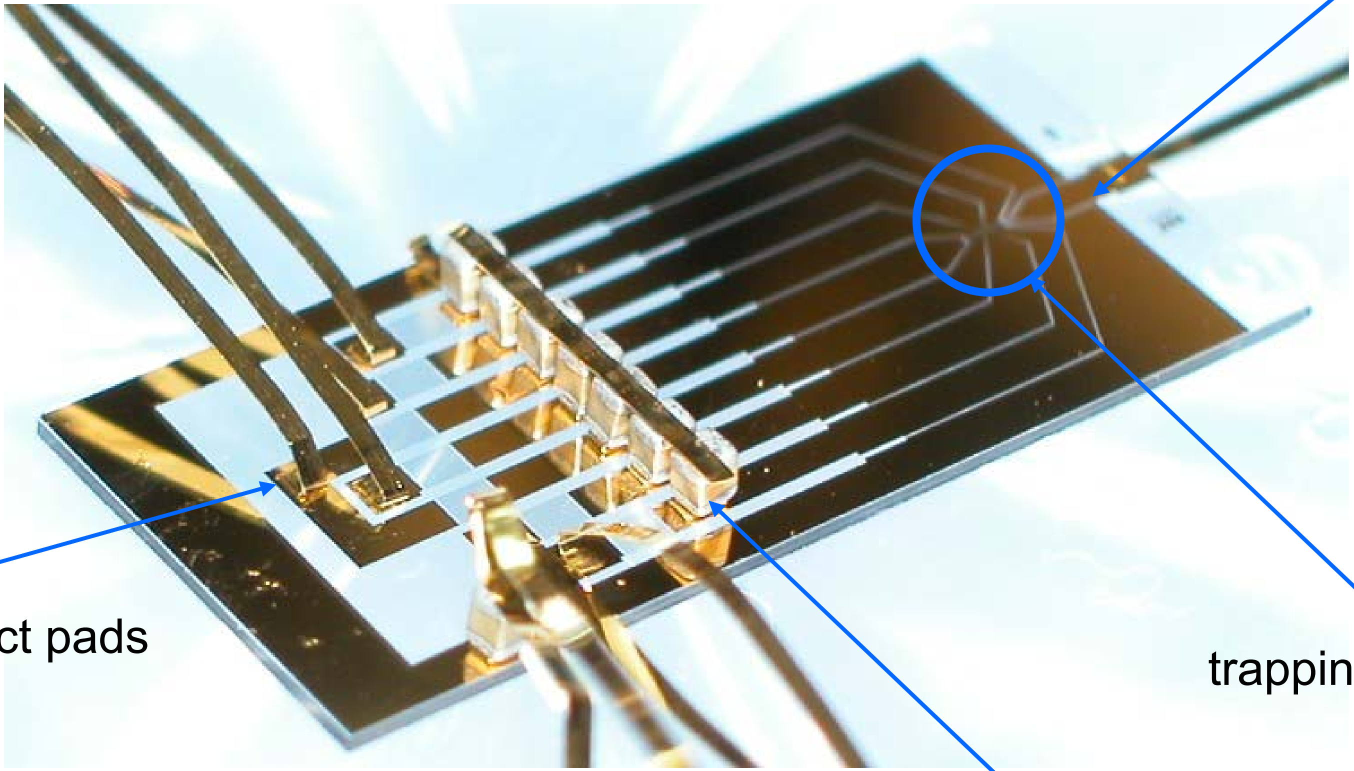


axial cross section

S. Seidelin et al., quant-ph/0601173

Planar Trap Chip

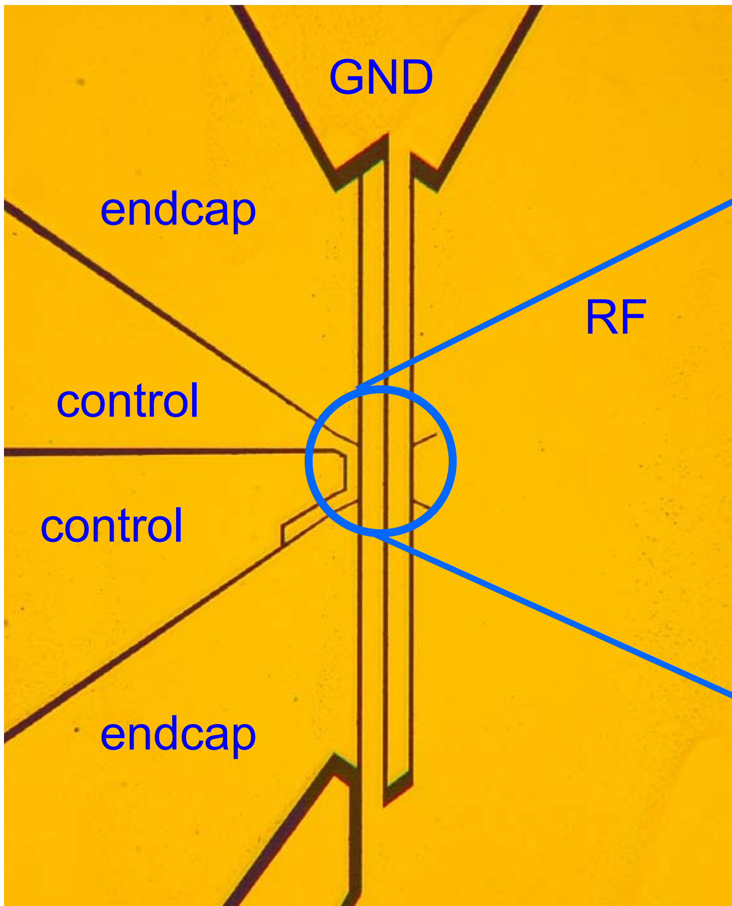
Gold on fused silica



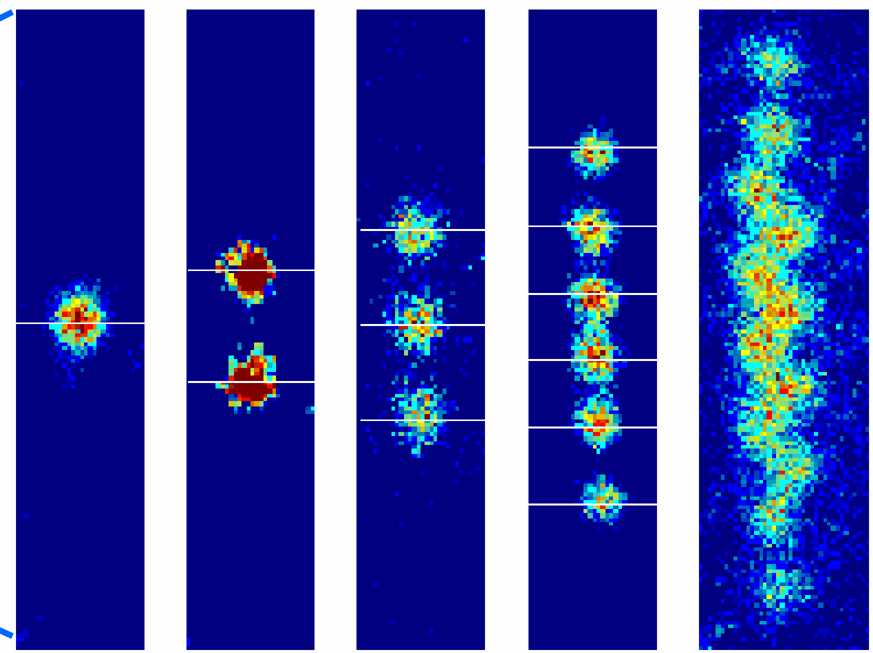
John Chiaverini, Signe Seidelin, see poster T02

Planar Trap Chip

Magnified trap electrodes



CCD pictures of strings of Mg^+ ions
(trapped 40 μm above surface)

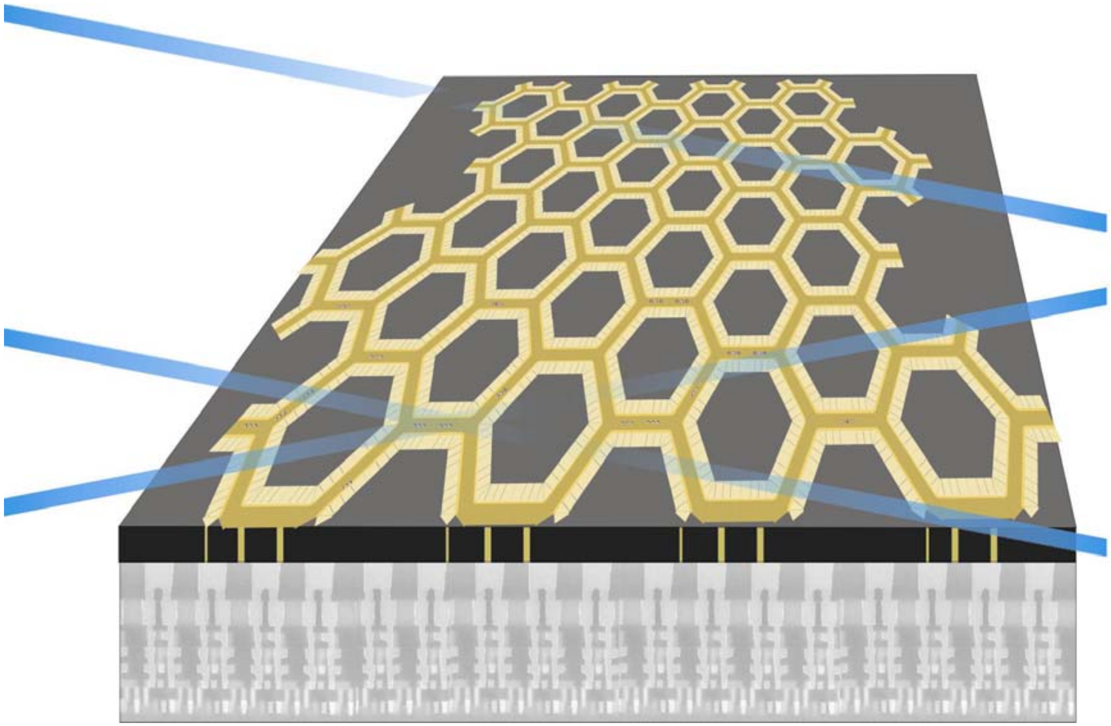


Estimated heating rate <5 quanta/ms

John Chiaverini, Signe Seidelin, see poster T02, also quant-ph/0601173

The future: Integrated ion chips ?

Large trap array, how to turn corners, see also poster T01



Multiple laser beams in plane of ions

Vias

CMOS control electronics below surface trap

"Solid state" with the bulk separated from qubits

ARDA/NSA Fabrication initiative:
Collaborations with Lucent Technology and Sandia Nat. Lab., see other talks

Multi-Qubit Algorithms

Towards Heisenberg-Limited Spectroscopy with Multiparticle Entangled States,
Science **304**, 1476 (2004).

Deterministic quantum teleportation of atomic qubits,
Nature **429**, 737 (2004).

Quantum Dense Coding with Atomic Qubits,
Phys. Rev. Lett. **93**, 040505 (2004).

Realization of quantum error correction,
Nature **432**, 603 (2004).

Enhanced Quantum State Detection Efficiency through Quantum Information Processing,
Phys. Rev. Lett. **94**, 010501 (2005).

Implementation of the Semiclassical Quantum Fourier Transform in a Scalable System,
Science **308**, 997 (2005).

Creation of a six-atom 'Schrödinger cat' state,
Nature **438**, 639 (2005).

In progress: *Entanglement purification*, see also poster M25

Multi-Qubit Algorithms

Realization of quantum error correction,
Nature **432**, 603 (2004).

More algorithms: see poster M25

Why quantum error correction ?

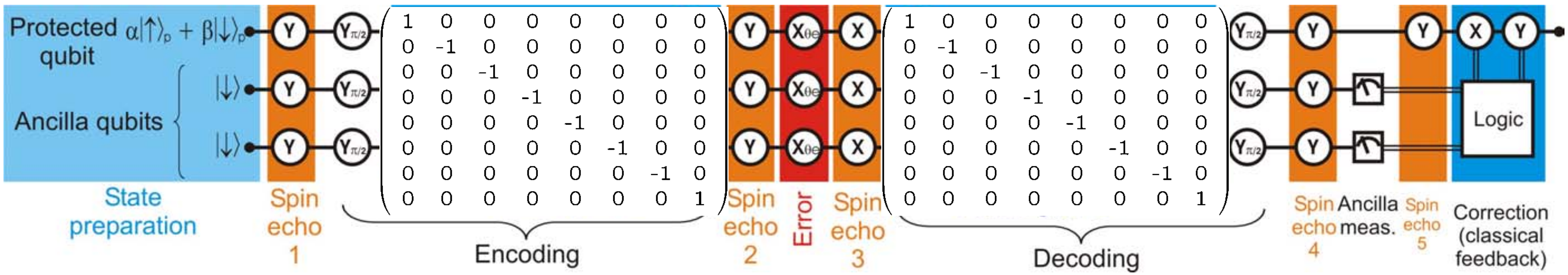
Quantum error correction upgrades large scale quantum computing from
“Totally hopeless”
to
“Theoretically not hopeless”

Will almost certainly be required in large scale computer

Threshold theorem: If individual operation errors are sufficiently small
we can do arbitrarily long calculations
(for more disclaimers, see e.g. Ike Chuang’s talk).

3 Qubit Bitflip Error-Correction

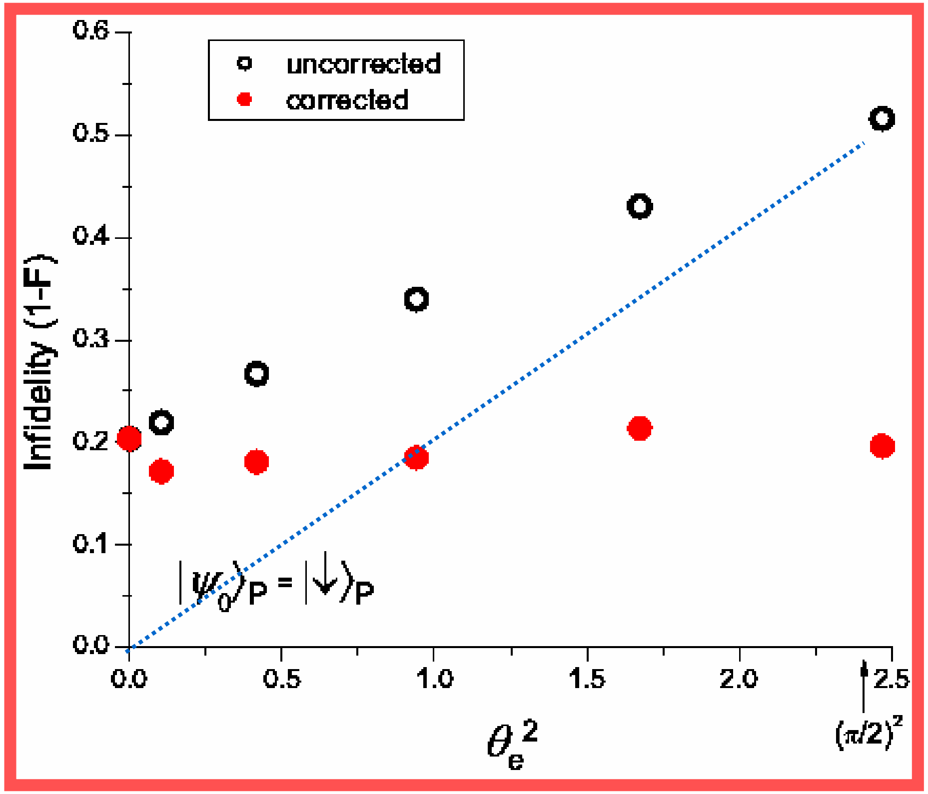
- experimental error correction with classical feedback from *measured* ancillas
- based on new stabilizer code with generators {ZZX,ZXZ} (no classical analog)

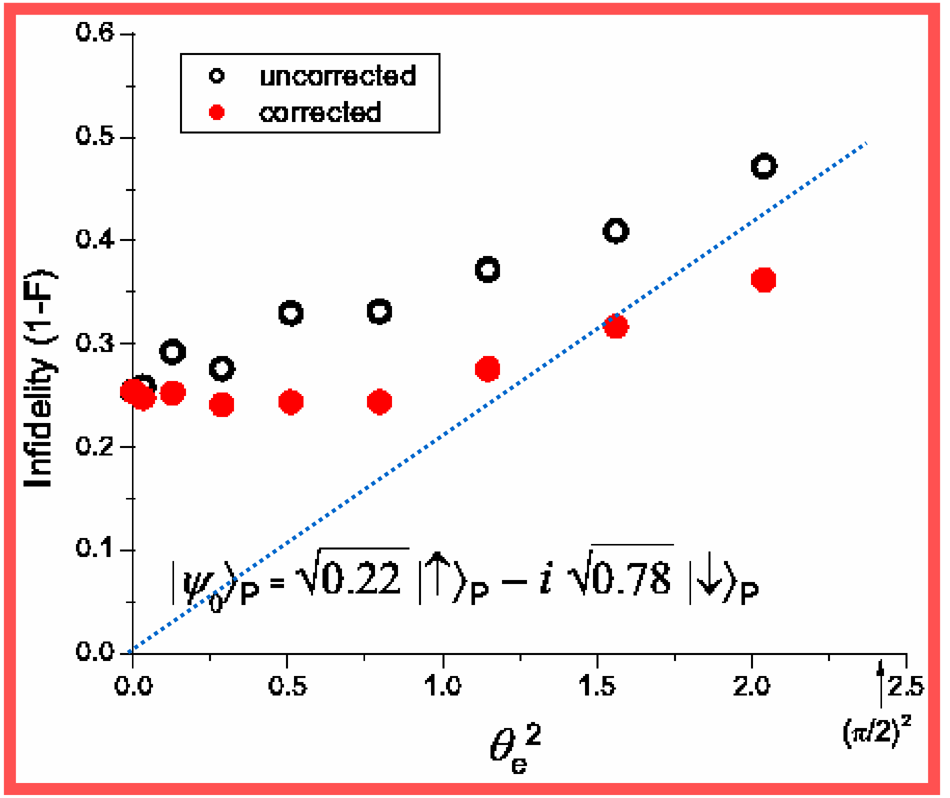


encoding/decoding gate (G) implemented with single step geometric phase gate

J. Chiaverini et al., *Nature,* **432**, 602 (2004)

Error-Correction Results





- Uncorrected infid. $\sim \theta_e^2$, corrected infid. $\sim \theta_e^4$

J. Chiaverini et. al. *Nature* **432**, 602 (2004)

Next steps towards scalability

Elements that need to be demonstrated in trap array:

1) Shuttle ions in 2D with minimal heating
2) DAC electrode control that combines speed with low noise/crosstalk
3) On chip/in vacuum multiplexing of electrode control
4) Ion reservoir to quickly replace lost qubits

Elements that need to be demonstrated in ion control:

1) Repetitive sequences with multi-qubit gates, movement and recooling
2) Fast motion/separation approaching the adiabatic limit
3) Multiplexing of laser interactions over several trap zones
4) Automated calibration of ion positions and Rabi frequencies

Elements that need to be demonstrated in ion readout:

1) Simultaneous readout in multiple zones (important for error correction and parallelism)